

VSS048

Advanced Heavy-Duty Engine Systems and Emissions Control Modeling and Analysis



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**2014 U.S. DOE Hydrogen Program and
Vehicle Technologies Program Annual
Merit Review and Peer Evaluation
Meeting**

June 16-20, 2014

OVERVIEW

Timeline

- Project start date: Oct. 2011
- Project end date: **Sept. 2014**

Barriers*

- Risk aversion
- Cost
- Constant advances in technology
- Computational models, design, and simulation methodologies

**from 2011-2015 VTP MYPP*

Budget (DOE share)

- FY12 funding: \$325k
- FY13 funding: \$300k
- FY14 (current expected) funding: \$340k

Partners

- Meritor, Inc. (CRADA)
- DOE Advanced Engine Crosscut Team
- CLEERS Collaborators
- Oak Ridge National Laboratory
 - Fuels, Engines, & Emissions Research Center
 - Power Electronics & Electric Machines Research Center
 - Center for Transportation Analysis

OBJECTIVE: Reduce petroleum consumption for heavy and medium duty trucks through advanced powertrain hybridization

“WHY”

- Hybridization of truck and bus powertrains has the potential to greatly reduce fuel consumption, criteria pollutants, and greenhouse gases.
- Like conventional trucks and buses, hybrids must satisfy both fuel efficiency and emissions constraints*.
- The most fuel efficient MD and HD engines are advanced diesels, which require specialized lean exhaust aftertreatment for emissions control.
- Integrating aftertreatment, advanced engines, and electrical systems is an extremely complex problem; the parameter space is too large to be solved with experiments alone.

“HOW”

- Develop and validate accurate component models for simulating integrated engine, electrical, and lean aftertreatment systems in diesel trucks and buses.
- Evaluate the merits of basic alternative engine-electric-aftertreatment configurations and generic control strategies under realistic MD and HD drive cycle conditions.
- Identify promising R&D opportunities, critical factors, and key data needs for improving MD and HD truck drive-cycle energy efficiency, fuel mileage and emissions.

* Develop and demonstrate **an emissions compliant engine system** for Class 7-8 highway trucks that achieves 50% brake thermal efficiency in an over-the-road cruise condition, improving the engine system fuel efficiency by about 20% (from approximately 42% thermal efficiency today). (2015)

– 21st Century Truck Roadmap:

(http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/21ctp_roadmap_white_papers_2013.pdf)

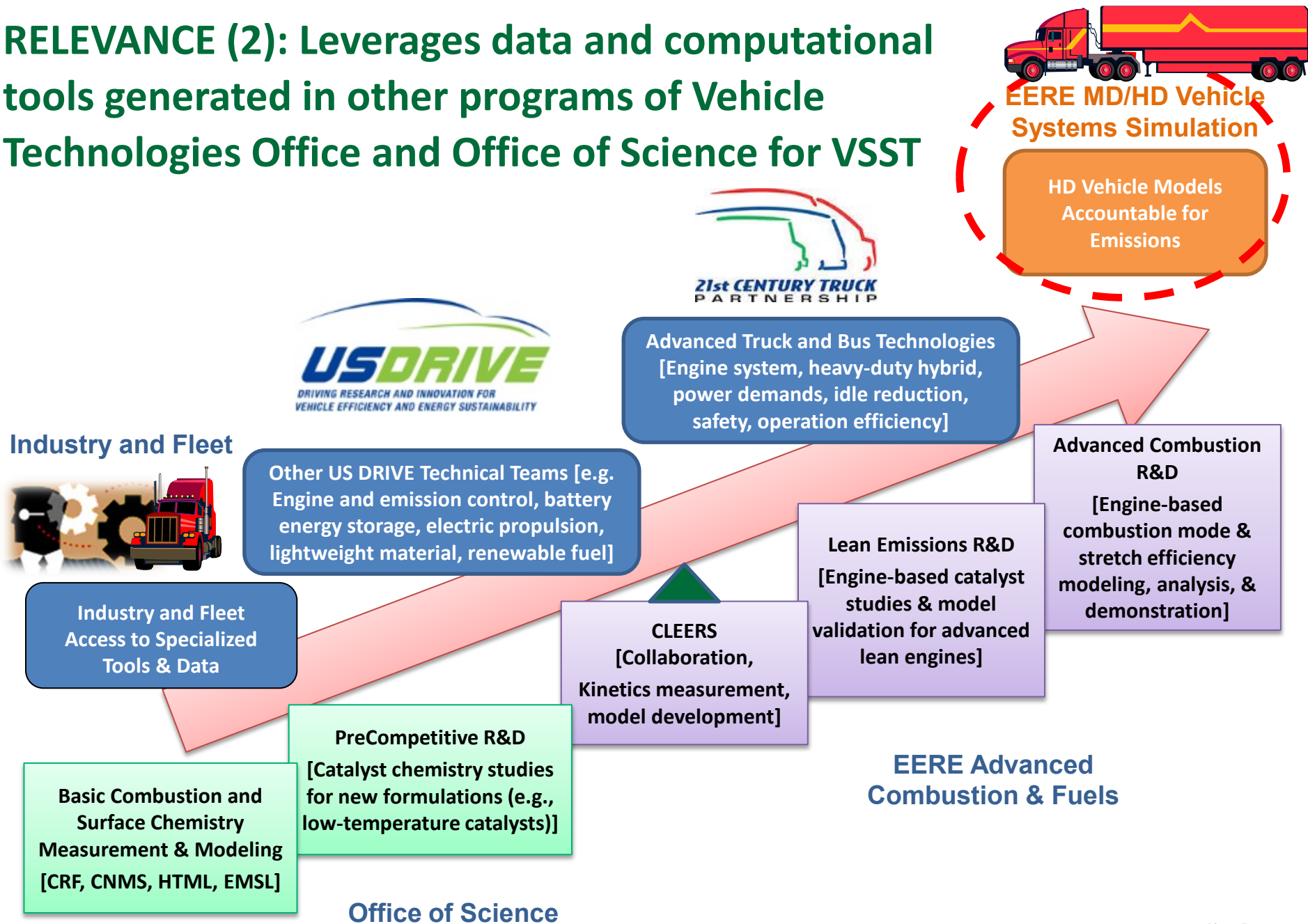
RELEVANCE (1)*

- **Supplies basic information to 21st Century Truck Partnership:**
 - Integrated heavy vehicle full system models for assessing the impact of drive cycle transients.
 - Quantitative measures of the impact of idle and accessory loads on fuel efficiency.
 - Tools for comparing emissions from different hybrid configurations (e.g., parallel vs. series).
- **Directly contributes to 3 VSST cross-cutting activities:**
 - Modeling and simulation; component & systems evaluations; heavy vehicle systems optimization.
- **Indirectly assists VSST laboratory and field vehicle evaluations.**
- **Addresses the following VSST Barriers:**
 - **Risk aversion:** Integrates physically-based simulation and analysis with experimental measurements to help plan and guide experiments, minimize empiricism.
 - **Cost:** Leverages ORNL VSI lab, data and models from other VTO projects, CLEERS, DOE-OS.
 - **Constant advances in technology:** Accounts for latest pre-competitive advanced high efficiency combustion and lean aftertreatment information and regulatory impacts (e.g. Tier 3) .
 - **Computational models, design, and simulation methodologies:** Combines fundamental physics and chemistry with best available laboratory and dynamometer data to maximize accuracy.

***Reference: Vehicle Technologies Multi-Year Program Plan 2011-2015:**

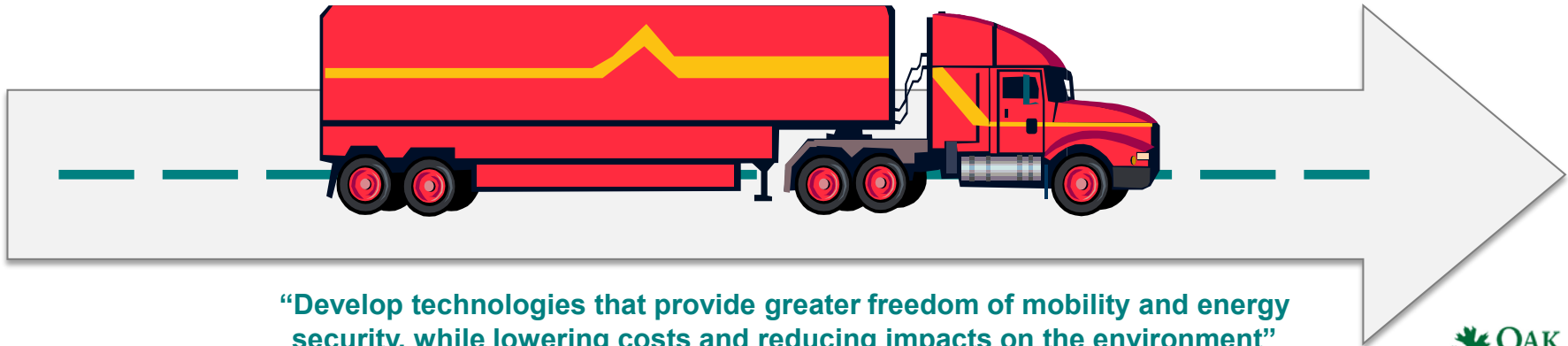
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

RELEVANCE (2): Leverages data and computational tools generated in other programs of Vehicle Technologies Office and Office of Science for VSST



FY2014 MILESTONE

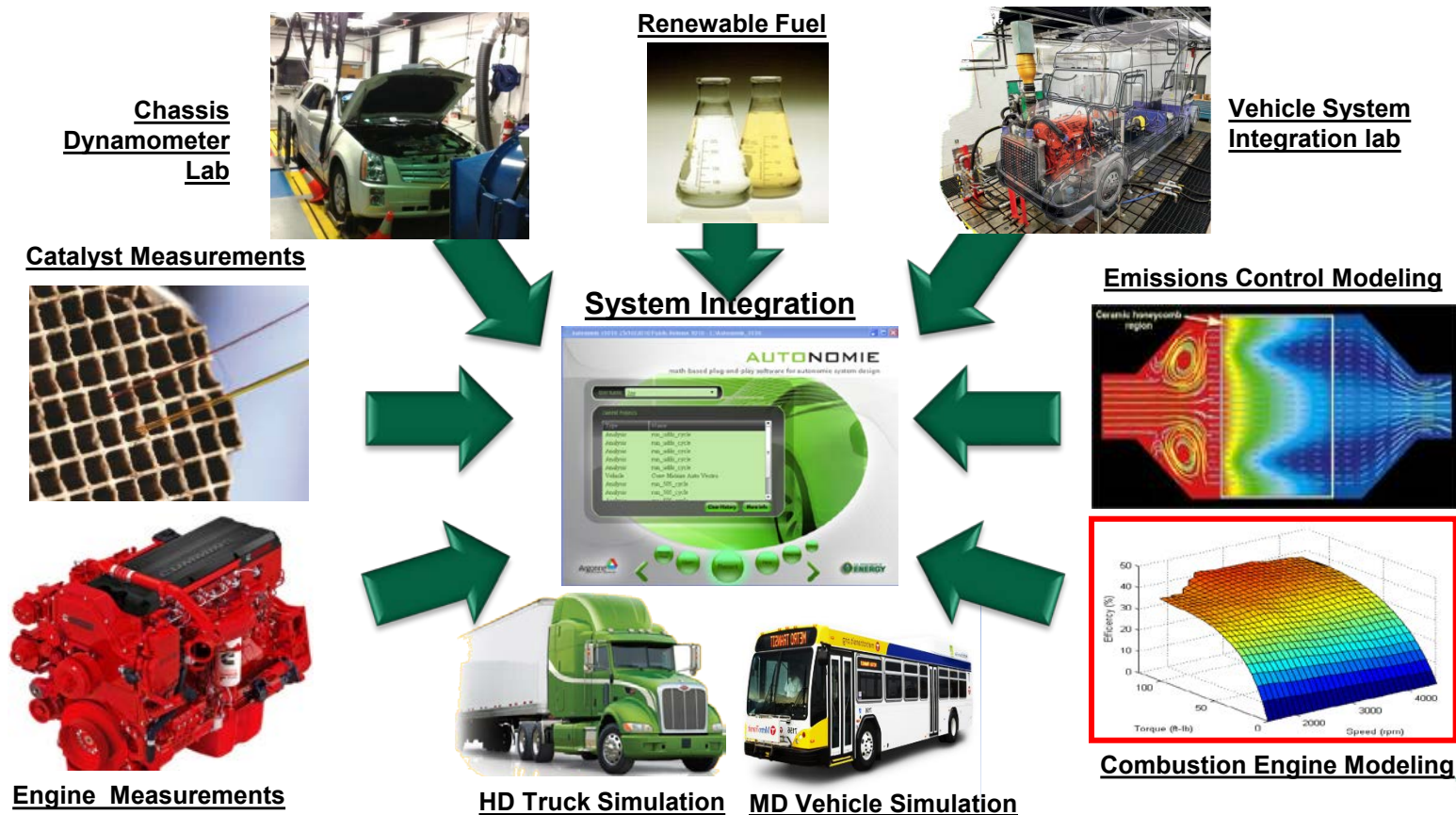
Date	Milestones	Status
March-2014	Data collection and characterization of accessory loads	Complete
March-2014	Bus hybrid trend simulation and comparison	Complete
Sept-2014	HD accessory loads modeling and sensitivity simulation at vehicle systems level	On track
Sept-2014	Refinement and updating HD engine and aftertreatment models using VSI measured Data	On track



“Develop technologies that provide greater freedom of mobility and energy security, while lowering costs and reducing impacts on the environment”

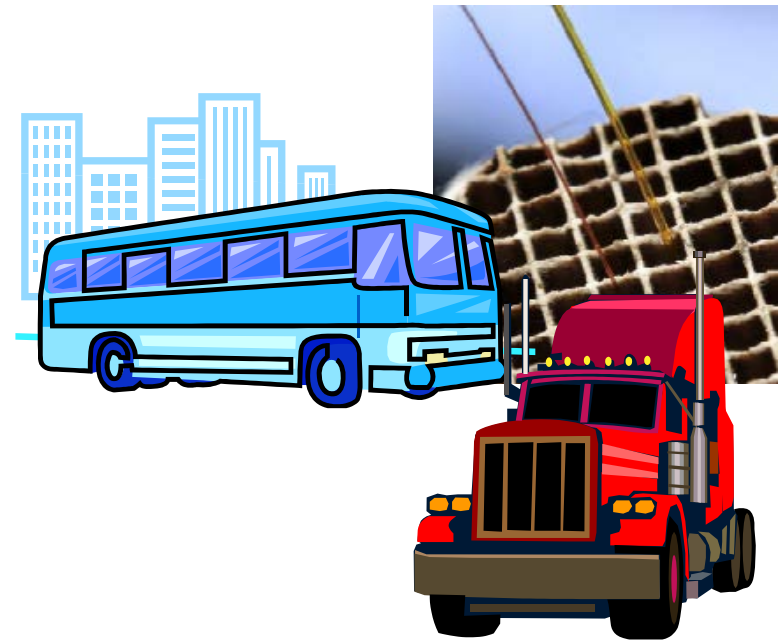
APPROACH: Link component models in integrated MD/HD simulations

- Engine and aftertreatment component models
 - Steady-state and transient MD/HD engine maps from dyno measurements and advanced combustion models.
 - Physical parameters, global kinetics for LNT, SCR, DOC, DPF, passive adsorber devices.
 - Links to other critical component models , e.g. battery, auxiliary loads, fuel, waste heat recovery.
- Adopt data and models from other ORNL projects, industry, national labs, open literature.
- Evaluate advanced MD/HD hybrid hardware configurations, generic control options.
- Provide basic models to Meritor CRADA and utilize CRADA data for model improvements.



ACCOMPLISHMENT SUMMARY : Developed new models & integrated with previous models to address hybrid engine/emissions challenges

- **Improved component and drive cycle models linked with Autonomie**
 - 3 new reference urban MD drive cycles
 - Improved CDPF CO/HC oxidation kinetics
 - New HD auxiliary load models
- **Used models to assess hybrid MD bus trends**
 - Benefits of hybrid vs. conventional for different drive cycles
 - Fuel economy & emissions control vs. electric system size
- **Used models to identify MD and HD challenges and opportunities**
 - Detailed energy loss distribution estimated for conventional and hybrid MD and HD vehicles



Previous work in 2013

- Preliminary 2010 HD engine map
- Aftertreatment configuration (DOC/DPF/SCR)
- Class 8 HD parallel hybrid simulations

ACCOMPLISHMENT (1): Developed real-world drive cycles for advanced engine and aftertreatment performance evaluation

- 1 year of ORNL MD truck data (12 MD buses and trucks)
 - H.T. Hackney wholesale delivery trucks
 - Knoxville Utilities Board vehicles
 - Knoxville Area Transit (KAT) buses

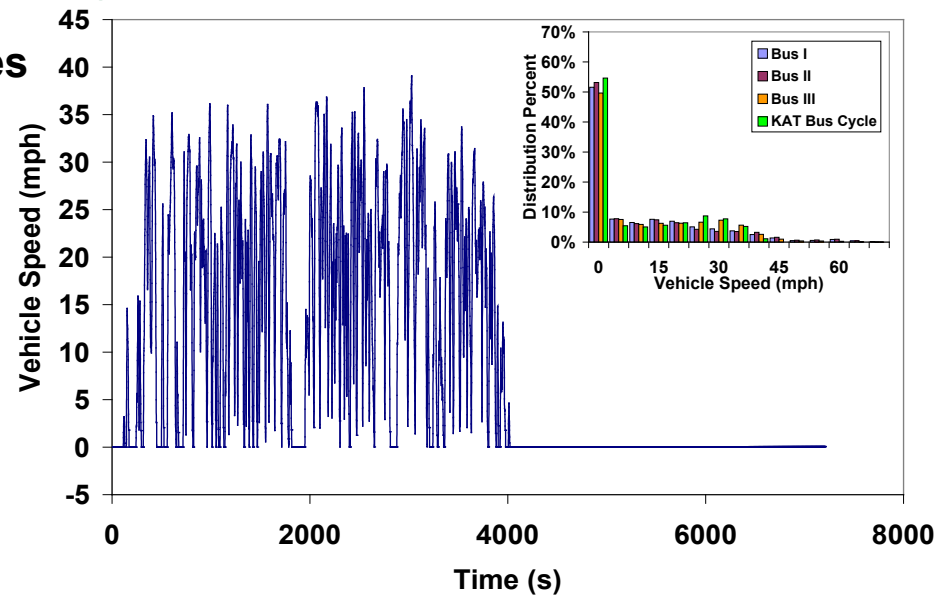


Deliver truck: H.T. Hackney
2007 International 8600

Utility vehicle:
2010 International
DuraStar



KAT transit bus: 2005
Optima LF-34 buses

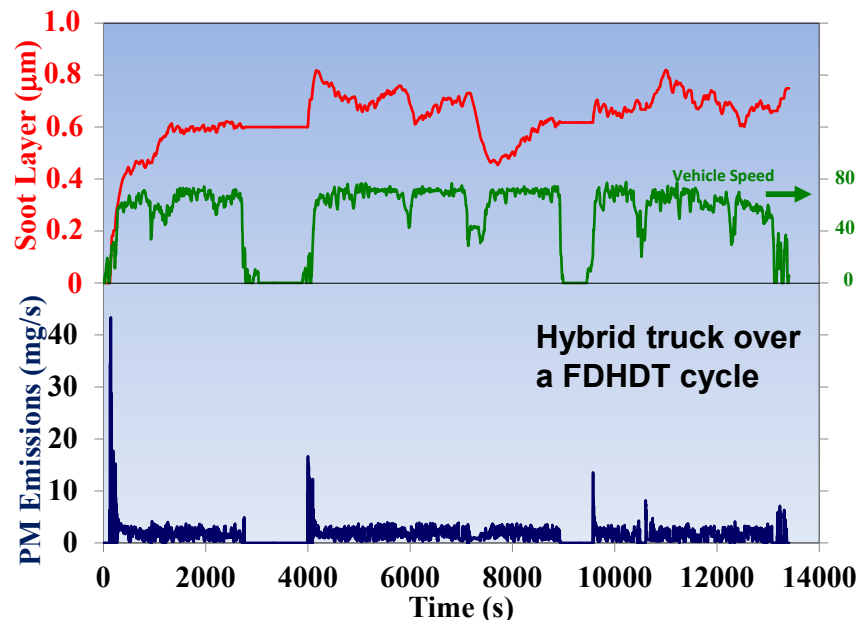
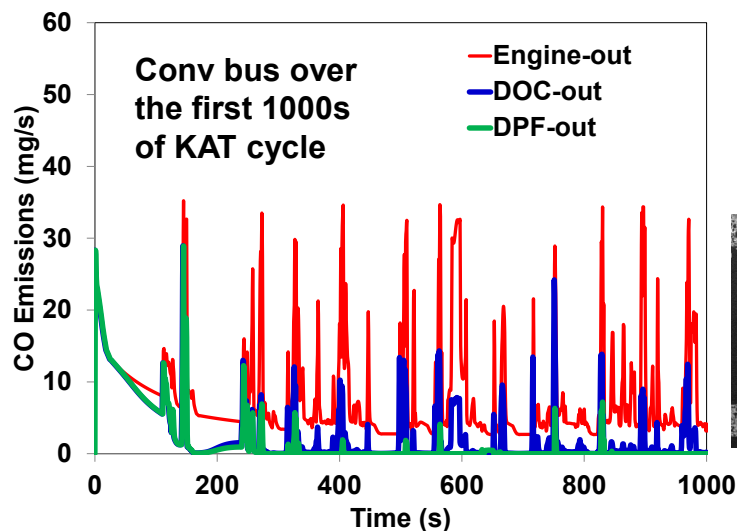


New cycles reveal important power demand details for delivery & transit vehicles

- Example KAT bus data
 - 3 identical buses on different routes
 - Similar speed and acceleration for all 3
- 2 distinct driving modes observed
 - Frequent stop-and-go period dominated by low speed and acceleration
 - Extended idling (more than 50% of the time, much of it at single stops)

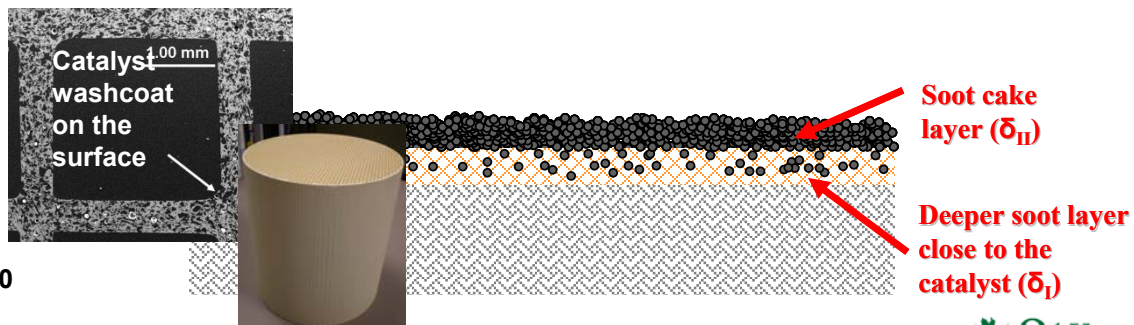
ACCOMPLISHMENT (2): Improved CDPF model

- **Catalyzed diesel particulate filter (CDPF)**
 - Critical for PM, CO, HC, & NO_x control
 - Catalyst reduces regeneration fuel penalty (significant passive regen @ 250°C)
 - Important since CO & HC higher with some advanced combustion
- **ORNL CDPF model is based on CLEERS data**
 - PM deposition in filter wall & surface layer
 - 1-step global kinetics for CO & HC oxidation
 - CO, HC, & NO oxidation in filter impact subsequent NO_x reduction & tailpipe CO/HC
 - Reveals CO generation can be high during passive regen



Improved CDPF model gives more accurate prediction of CO, HC, PM, & NO_x control

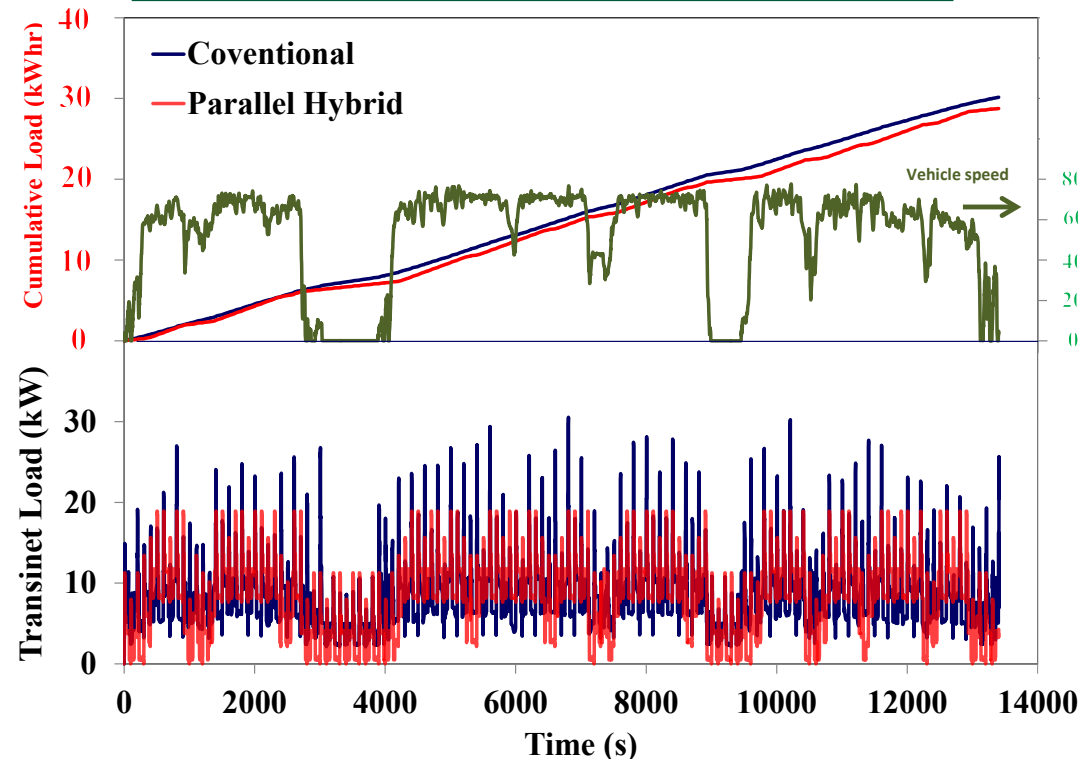
- Especially important for assessing impact of passive regen in reducing fuel penalty while still meeting emissions constraints



ACCOMPLISHMENT (3): Evaluated engine performance with respect to transient auxiliary loads

- Conventional and hybrid accessory loads distinguished
 - Different accessory components
 - Different 'On' times
- Improved over previous HD auxiliary model
 - Constant load for all components together
 - Lack physical meaning and accuracy

Example simulated transient load in HD trucks



Auxiliary load comparison

Conventional HD Truck Auxiliary Component Loads

(Blue: ME; Red: EE)

Air Break Compressor

Engine Fan

Air Conditioning Compressor

Lubricant Oil Pump

power steering

Coolant Pump

Transmission Fluid Pump

Electrical Control & Loads

Hybrid HD Truck Auxiliary Component Loads

(Blue: ME; Red: EE)

Air Break Compressor

Engine Fan

Air Conditioning Compressor

Lubricant Oil Pump

Power steering

Coolant Pump

Transmission Fluid Pump

Battery Cooling Fan

Electrical control

Electrical Control & Loads

New model provides more accurate estimates of auxiliary energy losses

Example- For class 8 long-haul truck (16ton-35ton):

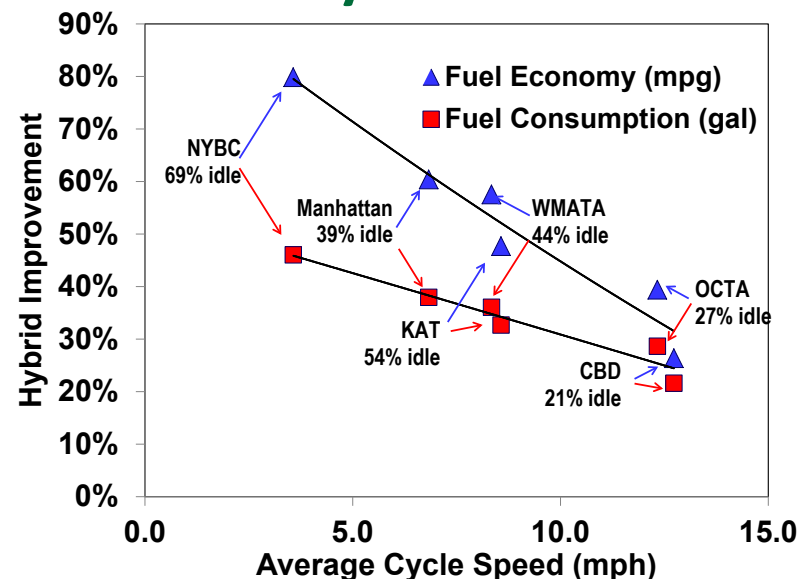
- Highway auxiliary load \approx 5%-7% tractive energy
- City auxiliary load \approx 10%-18% tractive energy

ACCOMPLISHMENT (4): Assessed energy loss distribution for hybrid vs. conventional transit buses over 6 different drive cycles

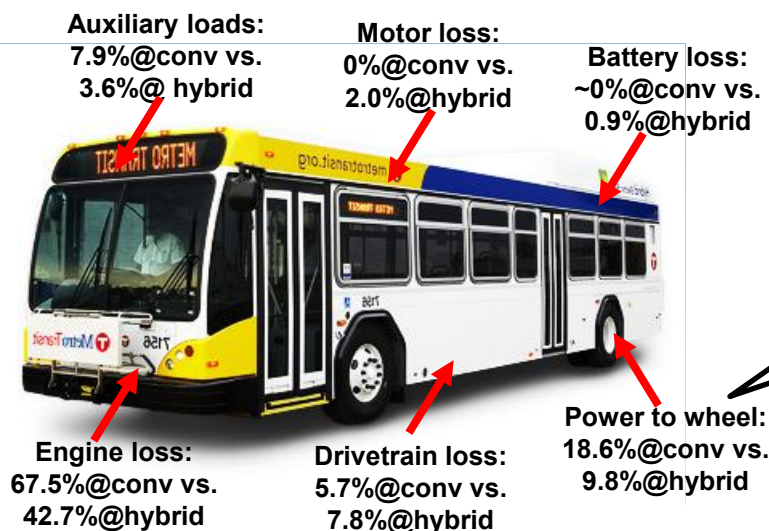
- Example case study
- 11,636 kg conventional weight + 200 kg for hybrid
- 5.9L diesel engine & 5-speed manual transmission
- 120 kW Motor, 140 kW battery w/ sustainable charging strategy
- Drive cycles: CBD, OCTA, MBC, WMATA, NYBC, KAT
- Conv powertrain calibration: 4.28mpg simu vs. 4.36 mpg exp

Observations

- Hybrid bus exhibits fuel saving for all 6 city drive cycles
- Hybrid benefits greater for lower speed cycles
- Benefits due to: higher engine efficiency; idle and auxiliary load reduction; braking energy recovery

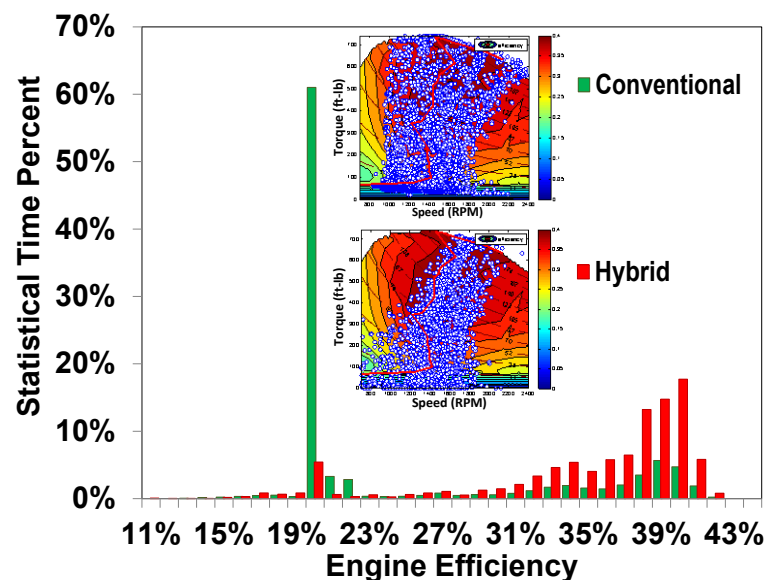


Example bus energy loss over the KAT cycle



Detailed energy losses clarify high impact opportunities for hybridization

**Braking loss
12.9% @ conv vs.
4.7% @ hybrid**

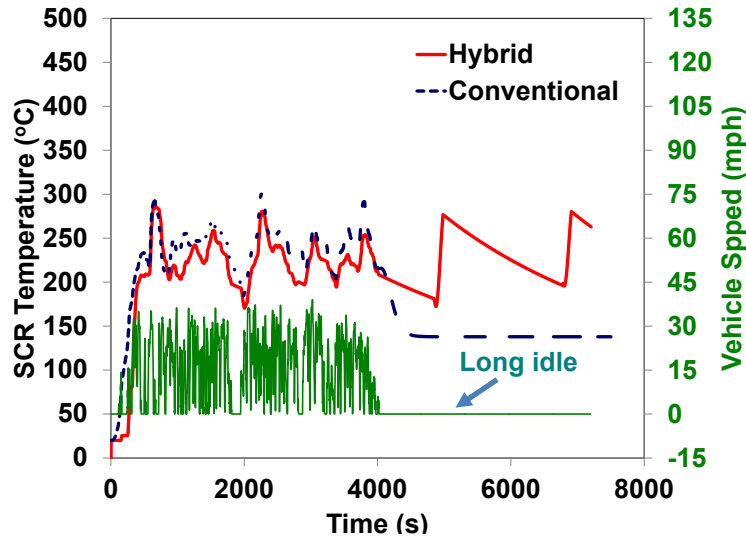


ACCOMPLISHMENT (5): Assessed impact of motor and battery size on hybrid bus fuel economy and emissions in city driving

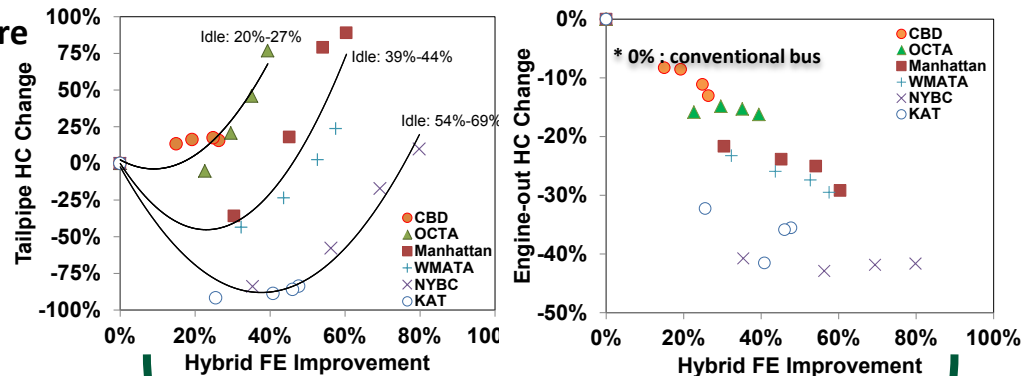
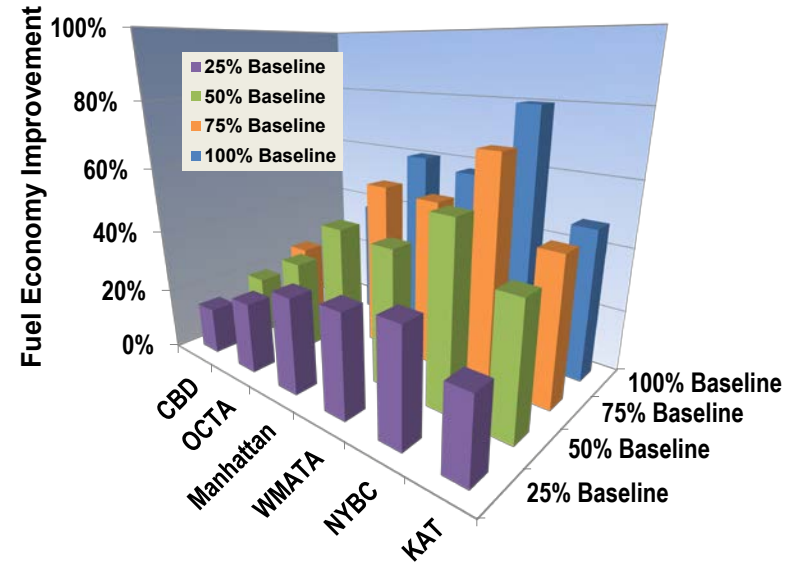
- Example case study - pre-trans parallel
- 11,636 kg conventional weight and 200 kg hybrid penalty
- 5.9L diesel engine & 5-speed manual transmission
- 25%-100% size of 120 kW Motor and 140 kW battery
- Drive cycles: CBD, OCTA, Manhattan, WMATA, NYBC, KAT
- Aftertreatment: 2.3L DOC, 7.7L CDPF, 9.7L urea-SCR

Observations

- Smaller motor/battery lowers fuel economy benefit
- Engine-out emissions monotonically decrease with increased hybridization
- Tailpipe emissions don't track engine-out due to sensitivity of aftertreatment catalyst to temperature



Impact of hybrid on catalyst temperature depends on drive conditions (The case is KAT cycle)



Simulations revealed there may be an optimal level of hybridization, where emission constraints can still be met

Responses to Previous Year Reviewer Comments

- One reviewer asked whether the models were public domain or internal project use only. The reviewer also ask whether there is a tool helping link these for the broader community.
 - *ORNL response: Technical details to the tools developed in this project have been published in the open literature, which anyone can adapt to their needs. Our project priority is to identify system sensitivities and trends for different advanced engine-aftertreatment combination, instead of generating software.*
- One reviewer commented that it appeared we were using old (2010) engine calibrations, an unrealistic engine control strategy, and not accounting for engine transients.
 - *ORNL response: Our role in this project is to utilize unique DOE resources to help our industry partners identify technical issues and opportunities where they can most effectively concentrate their efforts. Thus we have restricted ourselves to non-proprietary engine data so that all our methods and results can be made fully public. As far as we aware, the 2010 engine is the latest non-proprietary data available. On the other hand, we make exceptional efforts to do engine transients and have published details about our approach for including the effects of transients. We regret if this has not been made clear.*
- One reviewer commented that the alternative hybrid drivetrains, waste heat recovery and control strategy variations were needed earlier to support other projects such as SuperTruck.
 - *ORNL response: The highest priorities for this project were centered on accurately analyzing the interactions between advanced combustion engines and emissions. Hybrid control strategies are being addressed by other parallel projects. We agree waste heat recovery may be important. However, due to the evolving technical challenges associated with emissions from advanced engines (e.g., the Tier 3 emissions standards), it was not possible to address waste heat recovery.*

COLLABORATION AND COORDINATION

- **CLEERS Collaboration (ACE022)**

- Multiple engine OEMs, suppliers, universities, national labs.
- DOE Advanced Engine Crosscut Team.
- USDRIVE Advanced Combustion and Emissions Control Tech Team.



- **National Laboratories, University and other research Institute**

- NREL and ANL
- Southwest Research Institute
- West Virginia University



- **Related ORNL Activities**

- ORNL Medium & Heavy Truck Duty Cycle “real world” database (including grade).
- Cummins MD & HD Accessory Hybridization CRADA (VSS133)
- Impacts of Advance Combustion Engines (VSS140)
- Heavy duty powertrain optimization project (VSS141)
- NO_x Control & Measurement Technology for Heavy-Duty Engine (ACE032)
- Fuel Effects on Emissions Control Technologies (FT007)



PROPOSED FUTURE WORK

- **FY2014**

- Complete representative 2010 emission compliant HD engine map with transient parameters derived from ORNL VSI measurements.
- Complete refining and updating mechanical and electrical accessory load models utilizing measurements from open literature, ORNL VSI, and industry.
- Continue refining and updating diesel exhaust aftertreatment models with the VSI measurements for emerging commercial catalysts and emission control devices.
- Continue MD/HD drive cycle simulations for alternative hybrid powertrains over wider range of drive cycles.

- **FY2015**

- This project is scheduled to end at the end of FY14
- The tools developed in the project will be integrated into other projects including heavy duty powertrain optimization (VSS 141)

SUMMARY: Significant progress has been made toward providing critical information for optimizing fuel-efficient and emissions-constrained MD and HD hybrid powertrains

- **Successful implementation of advanced MD and HD powertrain technologies requires understanding of the complex interactions among emissions control, energy generation, utilization, and parasitic losses over drive cycles.**
 - Improved CDPF model provides more accurate results of CDPF performance
 - A HD auxiliary load model has been developed and implemented in Autonomie.
 - Three MD drive cycles were developed from the ORNL MD truck database.
- **The current simulation tools enable to explore options in powertrain and aftertreatment configurations along with hybrid controls for maximizing the benefits of hybridization in the MD and HD sectors.**
 - The benefits of bus hybridization depend on the drive cycles characteristics, especially idling time
 - Hybrid bus tailpipe emissions indicate complex behavior while the engine-out emissions decrease with the level of increased hybridization
- **We continue to expand and enhance the capabilities of our engine and aftertreatment models, together with other critical technology models, to improve the accuracy and flexibility of MD and HD vehicles.**

ACKNOWLEDGEMENTS

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Technical Back-Up Slides

Acronym Definitions

- **ACE- Advanced Combustion Engines**
- **ANL- Argonne National Laboratory**
- **CBD- Central Business District**
- **CDPF- Catalyzed Diesel Particulate Filter**
- **CLEERS- Crosscut Lean Exhaust Emissions Reduction Simulation**
- **CNMS- Center for Nanophase Materials Sciences**
- **CO- Carbon Monoxide**
- **CRF- Combustion Research Facility**
- **DOC- Diesel Oxidation Catalyst**
- **DPF- Diesel Particulate Filter**
- **EE- Electrical Energy**
- **EERE- Energy Efficiency and Renewable Energy**
- **EMSL- Environmental Molecular Sciences Laboratory**
- **FDHDT- Freeway Dominant HD Truck Cycle**
- **FT- Fuel Technology**
- **FY- Fiscal Year**
- **HC- Hydrocarbons**
- **HD- Heavy Duty**
- **HTML- High Temperature Materials Laboratory**
- **KAT- Knoxville Area Transit**
- **LNT- Lean NOx Trap**
- **MBC- Manhattan Bus Cycle**
- **MD- Medium Duty**
- **ME- Mechanical Energy**
- **MYPP- Multi-Year Program Plan**
- **NOx- Oxides of Nitrogen**
- **NREL- National Renewable Energy Laboratory**
- **NYBC- New York Bus Cycle**
- **OCTA- Orange County Transit Authority**
- **ORNL- Oak Ridge National Laboratory**
- **OS- Office of Science**
- **OVT- Office of Vehicle Technologies**
- **PM- Particulate Matter**
- **SCR/urea-SCR- Selective Catalytic Reduction**
- **UDDS Truck- Urban Dynamic Driving Schedule Truck Cycle**
- **VSI- Vehicle Systems Integration**
- **VSST- Vehicle and Systems Simulation and Testing**
- **VT- Vehicle Technologies**
- **WMATA- Washington Metropolitan Area Transit Authority**

List of References for the VSST models

- **Transient Engine Simulation Methodology**
 - Z. Gao et.al., A Proposed Methodology for Estimating Transient Engine-out Temperature and Emissions from Steady-State Maps, *Int. J. Engine Res.*, 11(2), 2010.
- **DOC/DPF/SCR Component models**
 - Z. Gao et.al., Simulation of Catalytic Oxidation and Selective catalytic NO_x Reduction in Lean-Exhaust Hybrid Vehicles, SAE paper 2012-01-1304 (DOC and SCR modeling).
 - Z. Gao et.al., Simulating the Impact of Premixed Charge Compression Ignition on Light-Duty Diesel Fuel Economy and Emissions of Particulates and NO_x, *Proc. IMechE - Part D: J. Automobile Engineering*, 227(1), 2013 (DPF modeling).
 - C.S. Daw et.al., Simulated Fuel Economy and Emissions Performance during City and Interstate Driving For a Heavy-Duty Hybrid Truck, *SAE Int. J. Commer. Veh.* 6(1) (DOC/DPF/SCR and new SCR parameters).
- **MD&HD Hybrid Vehicle Simulation**
 - C.S. Daw et.al., Simulated Fuel Economy and Emissions Performance during City and Interstate Driving For a Heavy-Duty Hybrid Truck, *SAE Int. J. Commer. Veh.* 6(1).
 - Gao et.al., Simulations of the Fuel Economy and Emissions of Hybrid Transit Buses over Planned Local Routes, SAE 2014-01-1562 (accepted by *SAE Int. J. Commer. Veh.* 7(1)).
- **Advanced Diesel Combustion Simulation**
 - Z. Gao et.al., Using a phenomenological Computer Model to Investigate Advanced Combustion Trajectories in a CIDI Engine, *Fuel*, 90, 1907–1918, 2011.

Assessed energy losses in conventional, series hybrid, and parallel hybrid buses and class 8 HD trucks

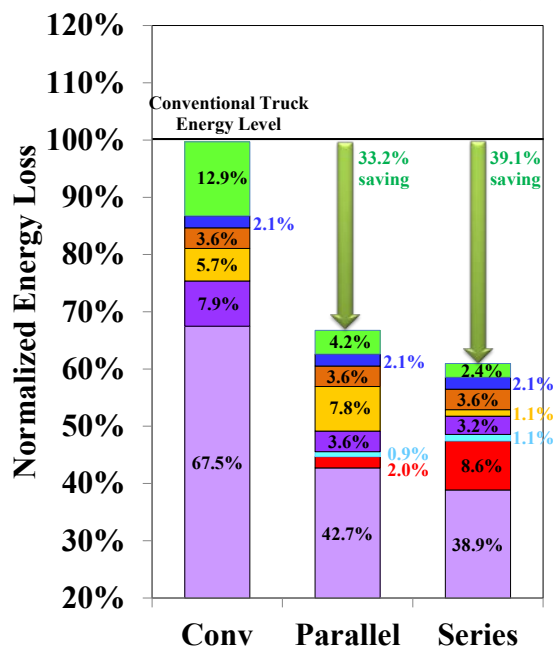
• Example case study

- 12,000kg series hybrid bus with 5.9L engine, 202kW motor/208kW generator/ 150, 220kW battery
- 25,500kg series hybrid with 2010 15L Cummins engine, 420kW motor/420kW generator/410kW battery
- Comparable conventional and parallel hybrid bus and truck adopted from our previous studies
- Drive cycles: KAT city drive cycle for bus, UDDS truck and ORNL freeway dominant HD truck (FDHDT) cycle for truck
- Aftertreatment: appropriate DOC, DPF, urea-SCR

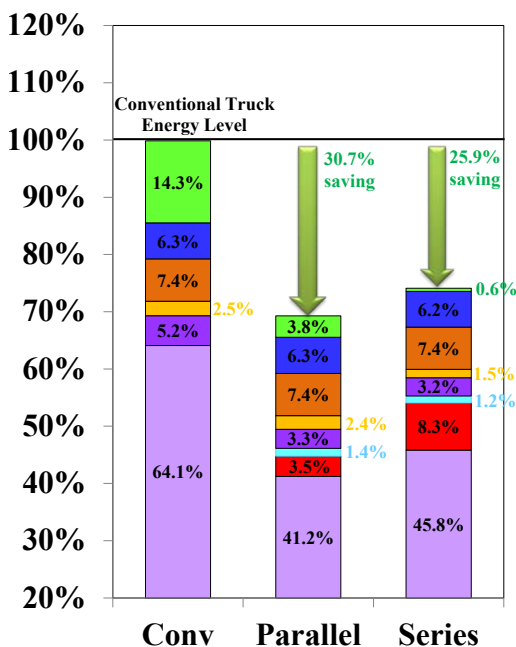
Revealed/confirmed several key points:

- **Series hybrid HD trucks have higher BTE, but lower hwy. FE.**
- **Engine-motor transfer losses offset higher BTE and braking recovery in series hybrid HD trucks on hwy.**
- **FE of parallel hybrid HD truck best in city & hwy.**
- **Series hybrid buses have best FE in city.**
- **Brake energy savings greater for both buses and trucks with city driving.**

MD bus over a KAT cycle



HD Truck over a UDDS truck



HD Truck over a FDHDT cycle

